Geotechnical Analysis Requirements

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Summary:

On several occasions the soil conditions have proven to be a key area for offshore wind farm projects, often this can result in disputes between the various parties involved over responsibilities. Despite the soil investigation being the owner´s responsibility, this responsibility is often delegated to a subcontractor. The importance of a thorough and well performed soil investigation cannot be understated for the design of offshore support structures. A good and well documented design basis that includes adequate geotechnical information will facilitate 'fast track' project development project of high quality with only minor variation orders to the contract; on the other had, a poorly carried out soil investigation can open up the project to delays and major variation orders, or a conservative and costly design.

This paper describes the design basis requirements for the geotechnical analysis, focusing on: the value of adequate soil investigations, the different investigation methods used, the importance of planning and execution, and concludes with DNV's experiences from existing offshore projects.

Key words: geotechnical, soil investigations, offshore support structures, design basis.

1. Introduction

Offshore wind turbine support structures are exposed to unusually high and complex levels of horizontal loading due to waves, wind, currents, and even ice impact. Thus the importance of performing the appropriate investigations requires special attention. Often soil investigations are essential for the design and development of an offshore wind farm project, if performed in a thorough manner, this can facilitate 'fast track' project development. However, on several occasions these soil investigations have had to be redone, resulting in project delays. The experience gathered from these previously installed projects includes a combination of the well-known pre-investigation and model methods, with new techniques. The aim is to contribute to an understanding of the formation, structure and physical performance of the subsurface, an understanding which is essential to ensure that any project intervention in the ground conditions will be carried out effectively, appropriately and predictably.

The soil investigations should reveal a geological model based on findings from geological studies, as wel as geophysical and geotechnical investigations. Detailed geotechnical investigations are performed and interpreted in order to provide a basis for the structural design of the selected foundation concept for the wind turbine, as well as laying of the cables.

Certification is recommended to begin concurrently with the data acquisition of soil, wind and wave conditions. An early consensus on the site specific loads will have a beneficial impact on the project

costs, reducing the risks to the designer and manufacturer of revised loadings and redesign caused by poorly predicted site conditions.

2. Procedures for Soil Investigations

Soil investigations provide the necessary soil data for detailed design. The soil investigations may be divided into:

- Geological Studies
- Geophysical Surveys
- Geotechnical Site Investigation

A geological study, based on the geological history, can form a basis for the selection of methods, and the extent of the geotechnical site investigation.

The scope of the geophysical investigations is to determine the three-dimensional distribution of the soil layers inside the project area (e.g. a wind farm and corresponding cable route), to survey the seabed, as well as investigating the seabed for unexpected objects.

A geophysical survey, usually based on seismic methods, can be combined with single soil borings to establish information about soil stratification and seabed topography over an extended area, such as that expected to be covered by contemporary wind farms.

Geotechnical investigations are carried out in order to verify and calibrate the geological model that is based on the geophysical survey. Borings should be located after consideration of the results of the geophysical profiling and the wind farm layout. The borings serve the purpose of confirming the geophysical mapping as well as and classifying the encountered soils. Furthermore, a goal of this investigation is to elucidate the geological/geotechnical characteristics of the interpreted soil layers. A geotechnical site investigation consists of in-situ testing of soil, and soil sampling for laboratory testing.

The extent and type of investigations depends on:

- Type and size of the wind turbine structure
- Complexity of the soil and seabed conditions
- Actual soil deposits
- Positioning and installation tolerances should also be accounted for

Soil investigations should provide relevant information on the soil to a depth below which the existence of weak formations does not influence the safety or performance of the wind turbine and its associated support structure and foundation.

Soil investigations normally comprise of:

- Site geology survey
- Topography survey of the seabed
- Geophysical investigations for correlation with soil borings and in-situ testing
- Soil sampling with subsequent laboratory testing
- In-situ test, e.g. Cone Penetration tests (CPT)

For details of soil investigations and soil sampling, reference is made to DNV-OS-J101 Sec.3 and DNV Classification Notes No. 30.4. For requirements for equipment, execution and reporting of soil investigations, reference is made to the following standards: NORSOK N-004, NORSOK G-CR-001, DIN 4020 and 4021, BSH No. 7004, and ISO 14688.

As relevant to the design, the geotechnical site investigations should provide the following types of geotechnical data for the soil deposits:

- data for soil classification and description of the soil
- shear strength parameters
- deformation properties, including consolidation parameters
- permeability
- stiffness and damping parameters for prediction of the dynamic behaviour of the wind-turbine structure

For further details reference is made to DNV-OS-J101 and Feld (2003).

3. Site Conditions

For the economical design of offshore support structures, it is of greatest importance to assess the site conditions (e.g. design soil parameters and design wave height) in an un-biased way, and based on state-of-the-art methods. Guidance for the determination of such parameters is given in the DNV-OS-J101 Standard. Requirements for soil investigations will also be given in the upcoming IEC 61400-3 (2005), which is currently a working draft.

Site conditions for offshore wind farm projects consist of all site-specific conditions which may influence the design of wind turbines, support structures and foundations that together constitute a wind farm. The site conditions include meteorological conditions, oceanographic conditions, soil conditions, seismicity, biology and various human activities.

The wind and wave climates are the most important site conditions for the loading of the wind farm structures, whereas the soil conditions are the most important site conditions for the capacities of their foundations.

Soil

Due to the loading scheme the importance of performing suitable site investigations is crucial for offshore wind projects.

For design and construction purposes the stratification of the individual soil units, the site-specific soil strength and the deformation properties are of particular interest. For this purpose, the DNV offshore standard presents guidelines for defining a tentative minimum soil investigation program, defining a program in terms of number and depths of soil borings and cone penetration tests. However such a program should always consider the complexity of the site, and may be altered during its execution.

Soil investigations (SI) shall provide relevant information about soil to a sufficient depth below which possible weak formations will not influence the safety or performance of the wind turbine, the support structure or the foundation. The sufficient depth and type of the soil investigations depends on the foundation type. In addition it is demonstrated how strength and deformation properties can be interpreted from the performed site investigations. Thus dependent on the SI

program, a model with geological description, geotechnical strength and deformation parameters can be identified for the entire project area. Following this, the model and associated parameters can be used for detailed design purposes.

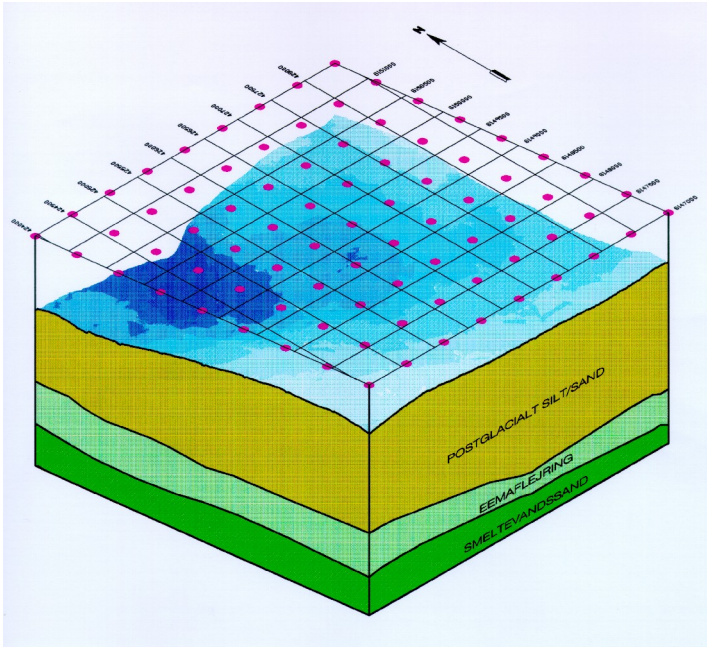

Figure 1 Geological/geotechnical model for the Horns Rev Offshore Wind Farm, Denmark.

4. Requirements to Soil Investigations

In principle, the site specific soil data is needed for all turbine positions within an offshore wind farm. This is particularly important when the conditions are not particularly homogeneous. Further requirements and guidance is given in DNV-OS-J101. •

To comply with the requirements and guidance given in DNV-OS-J101, the soil borings shall be carried out to a depth that will suffice for the detailed design of the respective foundations at the selected positions.

For piled foundations, this implies that the soil borings are to a depth at least equal to the pile length plus an additional half a pile diameter.

In case of gravity-based foundations, the soil borings should extend at least to a depth equal to the depth of any critical shear surface i.e., typically to a depth equal to the width of the foundation. However, there is also an additional requirement that possible weak formations below this depth do not influence the safety or performance of the wind turbine or associated support structure and foundation.

In order to comply with DNV-OS-J101, the geotechnical investigations at the actual site, comprising a combination of sampling with subsequent laboratory testing and in-situ testing should provide the following types of geotechnical data for all important layers:

- Data for soil classification and description
- Shear strength and deformation properties as required for the type of analysis to be carried out
- In-situ stress conditions

Lateral extent and lateral soil property variation of layers shall be examined and the laboratory test program shall be sufficient to perform the detailed design.

When designing a soil investigation program sufficient for design and construction purposes, the complexity of the site is to be considered; it is important to remember to use interpolation rather than extrapolation between borings. Furthermore, it is important to remember that any defined soil investigation program represents a tentative soil investigation program. A geotechnical engineer representing the owner or developer should be present onsite during the soil investigations, and depending on the findings during the soil investigations, may suggest changes to the soil investigation program during its execution.

For the cable route, deep soil borings are often not required. For the design of the cable trench, information about soil properties of importance, such as soil density and grain size distributions, can be obtained from vibrocore borings/ CPTs along the cable routes.

5. Time schedule for Soil Investigations and geotechnical design parameters

It is essential that the right information is available at the right time. Therefore, the information shall be achieved in a process closely related to the project evolution.

Ideally the program is carried out in compliance with the overall project time schedule. However, sometimes poor or inadequate soil investigations are performed resulting in the requirement to carry out additional soil investigations.

Lately the long delivery time for steel has sometimes resulted in the steel order being placed before the final soil investigation has been carried out, or at least before the final geotechnical design parameters have been established. Naturally this is far form the ideal situation, and based on previous project experiences, it should be acknowledged that the soil investigations are often key items for project discussion, and plays an important role in the entire project evolution.

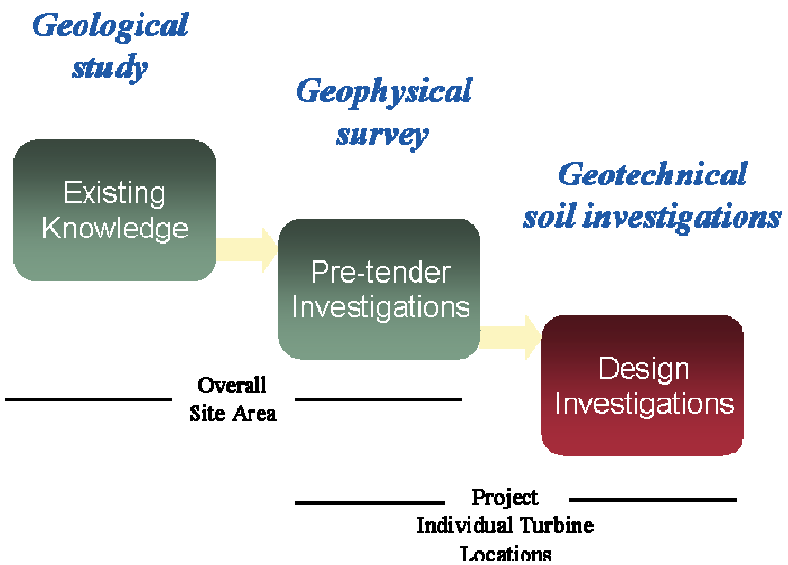

Figure 2 illustrating the ideal situation where soil investigations are carried out in conformity with the overall project time schedule.

6. Experience from Offshore Wind Projects

DNV has verified more that 25 offshore projects and the corresponding soil investigations. Normally, the executed soil investigation program consists of a geological desk study, a comprehensive geophysical survey and one or several rounds of geotechnical site investigations.

However despite this, sometimes the soil data is still quite limited. The consequence of this, dependent on the chosen foundation concept and associated design methodology, is that this limited soil information may serve as the design basis. Owing to the limited amount of soil data from the executed soil investigation program this may lead to a conservative design, as the limited amount of soil data will require the use of conservatively low strength and deformation values for bearing capacity analysis, as well as and upper strength values for the driveability analysis for driven pile foundations.

Dependent on who is responsible for the ground conditions and associated potential deviations and project risks, on several occasions owners/developers/contractors have carried out additional soil investigations to reduce the uncertainties related to the ground conditions, and thereby obtaining a more optimized design.

The presence of boulders and cobbles in glacial till and bedrock formations is an other ’hot issue‘ that is often discussed between the parties involved. The presence of these should be included in the design evaluation as it may be a design driver from an installation perspective.

It is current practice that either boreholes and/or CPT tests should be performed for each individual turbine location. Depending on the actual geology, and the result from supplementary investigations, this may not always be necessary. If the soil conditions and water depths are very homogeneous, being interpreted from seismic investigations, boreholes and CPT tests; it may be sufficient to perform boreholes or CPT tests for only a very few turbine locations. This depends on the spatial variability of the soil, soil parameters, and the robustness of the design approach. For calibration of the CPTs, a minimum of one CPT should be performed in close vicinity to one of the soil borings. The extent and type of detailed design investigations also depend on the chosen foundation concept. However the extent and type of detailed design investigations is also dependent on the chosen foundation concept.

7. Summary

On several occasions the soil conditions have proven to be of greatest importance and very often the causal factor in disputes between parties involved with the development of offshore wind farms. Therefore, from a cost and time perspective the importance of thorough soil investigations is crucial.

The soil investigations should reveal a geological model based on findings from geological studies, geophysical and geotechnical investigations. Detailed geotechnical investigations should be performed and interpreted in order to provide a base for the structural design of the chosen foundation concept for the turbines and associated laying of cables.

When designing a soil investigation program sufficient for design and construction purposes, the complexity of the site is to be considered. It is current practice that either boreholes and/or CPT tests should be performed for each individual turbine location. However, the extent and type of

detailed design investigations also depend on the selected foundation concept. The minimum requirements for a soil investigation program are given in DNV-OS-J101.

Certification is recommended to commence concurrently with data acquisition for soil, wind and wave site specific conditions, as an early consensus of the site specific loads will have a beneficial impact on the project costs, minimising the risks to the designer, manufacturer of a costly redesign due to revised loadings as a result of poorly predicted site conditions.

8. References

[1] DNV (2004): Det Norske Veritas, *Design of Offshore Wind Turbine* Structures, DNV Offshore Standard, DNV-OS-J101, June, 2004.

[2] Feld, T. (2003): Investigations for foundations of marine windfarms. 14. Tagung für Ingenieurgeologie Kiel 2003

[3] IEC-61400-3 Part.3 Design requirements for offshore wind turbines (working draft)